A Bragg Magnifier with Sub- μm Resolution Using High Energy Synchrotron Light

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Abstract. X-ray computer microtomography using synchrotron light (SR μ CT) has proven to be a highly powerful method in many fields of modern research as medicine, biology and material science. Presently used instruments, however, are limited to about $1\mu\text{m}$ resolution at a total efficiency of a few percent, due to the properties of the scintillator, the optical light transfer, and the CCD granularity. To overcome these limitations we have realized a novel approach based on extremely asymmetrical Bragg reflection. Our instrument, the "Bragg Magnifier" combines two asymmetrically cut Si crystals, mounted close to each other on two rotation and adjustment units. It is installed at the Materials Science Beamline of the Swiss Light Source (SLS). It operates at favorably high energies between 21 keV and 23 keV. In a first experiment using a human bone trabecula a two-dimensional magnification factor of 100×100 was achieved yielding a spatial resolution of 140nm .

INTRODUCTION

X-ray computer microtomography (SR μ CT) in conjunction with the availability of high intensity synchrotron light has opened new fields for modern non-destructive research in medicine, biology, and materials science. The most commonly used instrument consists of a sample holder, rotateable around a central axis and a detector unit. The synchrotron light beam passes through the sample and hits onto a scintillator crystal, which converts the X-rays to visible light. By means of a suitable optics it is transferred to a CCD detector which delivers the image information to a computer. When rotating the sample by small angular steps and continuously taking pictures, the stored information can serve to reconstruct a three-dimensional image of the sample [1-4]. The usual tradeoff between resolution and efficiency limits for a state-of-the-art detector of this type the resolution to $0.8\mu\text{m}$ at 0.5% efficiency when using 30 keV photons [5]. Alternative solutions as Fresnel plates [6] or refractive lenses [7] reach sub- μm resolution only in the energy range well below 20 keV while many applications request sub- μm resolution at energies above 20 keV maintaining a decent efficiency.

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To overcome these limitations we have realized a novel approach that combines sub- μm resolution with good efficiency at high photon energies: the Bragg Magnifier.

THE INSTRUMENT

The Bragg Magnifier is based on the principle of asymmetrical Bragg reflection applied at high energies. For convenience we briefly summarize the relevant results of dynamical theory.

Using the definitions of fig.1 and by choosing the adequate solutions of Maxwell equations for a medium with triply periodic electricity constant we obtain a rather complicated expression for the crystal response function [8,9,10]. A typical result is shown in fig.2 [11,12]. For the special case of a symmetrical reflection ($\alpha = 0$, $m = 1$) the diffraction width ω_s of an ideal crystal is

$$\omega_s = \frac{2}{\sin(2\theta_B)} \frac{r_0 \lambda^2}{\pi V} C |F_h| e^{-DW}$$

where $r_0 = 2.818 \cdot 10^{-15} \text{ m}$ is the classical electron radius, λ is the wavelength of the incident radiation, V is the volume of the unit cell, C is the polarization factor, θ_B is the Bragg angle, F_h is the crystal structure factor and e^{-DW} is the Debye-Waller factor. In this case the widths of the incident and the reflected beams are equal. This is no longer true for asymmetrical reflections ($\alpha \neq 0$, see fig.2). Here the dynamical theory yields for the diffraction width of the incident beam

$$\omega_0 = \sqrt{|m|} \cdot \omega_s$$

FIGURE 1. The basic definitions of asymmetrical reflection: with the Bragg angle θ_b and the asymmetry angle α between crystal surface and lattice planes the magnification m is determined.

FIGURE 2. The diffraction widths for Si (220) at 21.3 keV. With an asymmetry angle $\alpha = 8^\circ$ the curves for the reflected beam and the incident beam are given according to the above pattern code. For comparison we add the rocking curve for symmetrical reflection ($\alpha = 0^\circ$). Note that the index-of-refraction shift is different for each curve.

and for the diffraction width of the reflected beam

$$\omega_H = \frac{1}{\sqrt{|m|}} \cdot \omega_s.$$

It is obvious that for $m > 1$ the incident distribution is larger than ω_s which facilitates the matching to the photon beam divergence in order to obtain a high transfer efficiency.

Inspection of fig.2 reveals that for $m \neq 1$ there occurs an offset from Bragg's law which again is different for the incident and the reflected beam. For the cross sections of the incident beam S_0 and the reflected beam S_H Liouville's theorem requires $S_0 \cdot \omega_0 = S_H \cdot \omega_H$ and hence

$$S_H = |m| \cdot S_0.$$

An X-ray beam from the target area with a one-dimensional width S_0 hitting onto an asymmetrically cut crystal undergoes Bragg reflection with the cross section increased by a factor m in one dimension. The Bragg reflection at a second crystal, which is oriented so that the reflection planes are perpendicular with respect to the first one, produces a beam that in addition is magnified in the other dimension by m' (see fig.3). Thus the final result is an image with a two-dimensional magnification $m \cdot m'$. Usually the crystal planes and the asymmetry angles are chosen equal for both crystals so that $m = m'$. Finally this magnified X-ray image is converted by a scintillator crystal into the corresponding visible light distribution, which is handled by suitable optics and a

FIGURE 3. The principle of the Bragg Magnifier.

CCD camera in the conventional way. Recently such a device has been operated successfully at 12.3 keV reaching a resolution of about 1.2 μm [13].

Our instrument consists of two identical Si(220) crystals (size: 150x80x15mm³) with an asymmetry angle α of 8° [14]. To avoid stress and lattice plane distortions they were mounted by optical contacting on precision-polished glass plates [15], which have the same thermal expansion coefficient as Si. Those are fixed on top of two adjustment units that consist of two crossed swivels and a high-resolution goniometer [16] to rock the crystals. Its angular resolution of 0.05 arcs has to cope with the

FIGURE 4. The rocking curve of the Si(220) crystals measured at 8 keV ($\text{Cu K}\alpha_1$) corresponding width of the rocking curve of 0.3 arcs at 21 keV. As the rocking curves

of the two crystals are very similar in width and position (see fig.4) a symmetrical magnification in both dimensions can be expected.

In our instrument the magnified X-ray image is converted to visible light with high efficiency by a 300 μm thick CsI(Tl) scintillator (size: 35x35 mm²). The light is transferred by a 1:1 tandem optics [17] to the CCD chip [18] (2048x2048 pixels with 14 μm pitch).

Our device is designed to operate at the material science beam-line of the SLS [19], which produces a photon beam of 3×10^{13} photons/s in an energy range of 21 keV to 23 keV with a divergence of less than 20 μrad [20]. This number coincides very well with the acceptance angles of the Si(220) crystals so that finally 95% of the photon beam is accepted by the Bragg Magnifier. The experimental setup is shown in fig.5.

FIGURE 5. The experimental setup of the Bragg magnifier. The beam coming from the right is reflected by crystal 1 (only glass support and mounting from backside visible). The horizontal crystal 2 acts as a mirror of the adjustment unit above. In the black unit on the left side the scintillator is visible

FIGURE 6. A human bone trabecula seen at a magnification of 20x20 (upper part) and 100x100 (lower part). In both cases a boron fiber with a tungsten core was superimposed for calibration. On the right side (up) the glue for trabecula fixation is visible. The shadow on the left side (low) indicates an inhomogeneous illumination of the field of view. Clearly visible becomes the cellular structure of the trabecula.

RESULTS

The Bragg Magnifier was operated at the Materials Science Beamline of the SLS at energies between 21.1 keV and 22.75 keV. By adjusting the Si crystals accordingly, magnification factors between 20x20 and 100x100 have been achieved. As a first sample we investigated a human bone trabecula. For the calibration of the imaging properties we included in the target station a 100 μm boron fiber with a 15 μm tungsten core. Two typical images of this arrangement are shown in fig. 5. The magnification factor for the upper picture is 20x20, for the lower one it is 100x100, which yield an effective pixel size from 700x700nm² to 140x140nm². The corresponding field of view is 1440x1440 μm^2 and 280x280 μm^2 , respectively.

CONCLUSIONS

We have developed a Bragg Magnifier that operates with high efficiency at energies above 20 keV. Magnifications up to 100x100 have been reached so far, which yield resolutions down to 140nm. First tomographic pictures have been taken, the analysis of which is on the way. For improving the homogeneity of the image illumination at large magnifications we expect a step forward when the beam intensity of the SLS will be increased. An inspection of the present results indicate that edge-enhanced or phase-contrast investigations are feasible. We will study this feature in the next future.

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